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(Statement A)

A Colloid Engine Accelerator Concept Update

D. Kirtley
ERC, Inc.
Edwards AFB, CA

J. M. Fife
U.S. Air Force Research Laboratory
Edwards AFB, CA

A concept for a colloid engine with an electrodynamic linear accelerator is described. The charged particle source is a standard colloid engine with an extractor voltage that has an AC component. Downstream of the extractor, a series of accelerator gates are biased alternately with an AC voltage such that the charged droplets tend to remain in regions with positive electric fields. Since the droplet speed varies with their position in the accelerator, and the alternating voltage is of a constant frequency, the gate spacing must change with length. This variation in gate spacing may be determined analytically. This paper attempts to predict some of the potential performance advantages and disadvantages of such an engine through both mission analysis and first-order force analysis. In addition, the qualitative manufacturing and design performance sensitivities are investigated. Preliminary testing issues as well as higher level design ideas are explored, with special attention to potential problem areas.

Introduction

Small onboard electric propulsion (EP) thrusters have advantages over chemical engines in applications on small satellites, microsatellites, and nanosatellites. Several types of miniature EP thrusters are currently under development, including field emission thrusters, micro pulsed plasma thrusters, laser ablation thrusters, vacuum-arc thrusters, micro-ion thrusters, and micro-colloid engines. One problem with many of these devices is the requirement of high voltage or otherwise high power supply mass.

Electrostatic devices require a voltage in accordance with their propellant charge-to-mass ratio (q/m), and their specific impulse (I_{sp}). However, electrodynamic devices may not be limited by this constraint. This paper explores a concept for an electrodynamic particle accelerator with application to colloid engines.

Colloid Thruster Mission Benefits

Several interesting mission analysis have been done in order to try and justify the interest in colloid thrusters as a use for the base on this linear accelerator. One important point to note is that the current colloid thruster technology fares well against other comparable micro-satellite propulsion methods. This mission analysis does not characterize
Colloid Thruster Mission Benefits

Several interesting mission analysis have been done in order to try and justify the interest in colloid thrusters as a use for the base on this linear accelerator. One important point to note is that the current colloid thruster technology fares well against other comparable micro-satellite propulsion methods. This mission analysis does not quantitatively characterize the benefits of using an advanced acceleration method for performance enhancement. All missions analyzed are based off of the Stanford EMERALD Colloid Thruster :
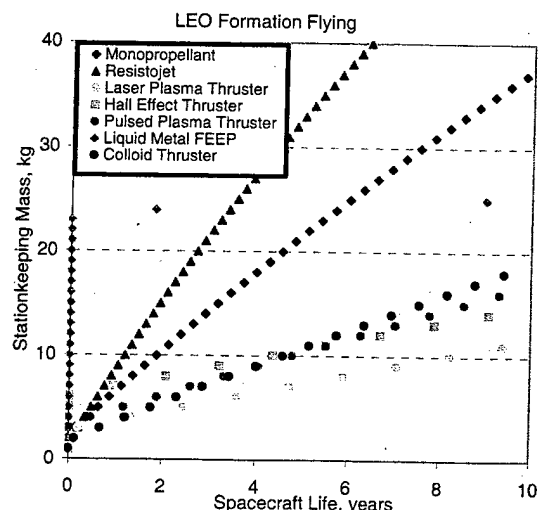9-pin   6Watt   315mN   600s   250gm

Fig. 1. Spacecraft orbit life time for a formation flying microsatellite mission.
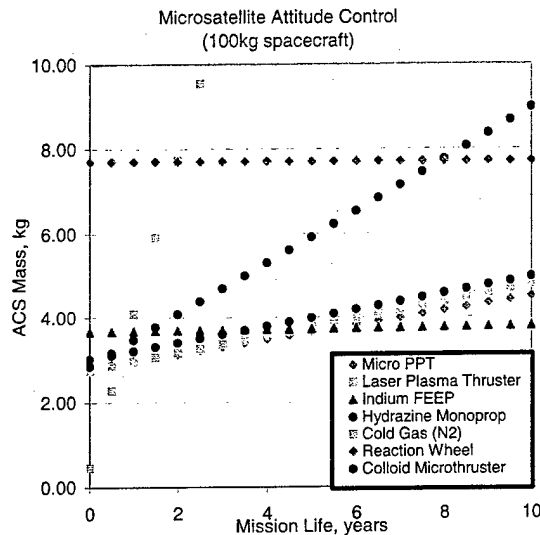
Microsatellite Attitude Control
(100kg spacecraft)

Fig. 2. Spacecraft altitude control.

The LEO formation flying is described by the following mission characteristics.

100 m/s/Year dV 600km Max 250Watt Power Budget

Next we look at an attitude control mission. This mission is characterized by once again, the Stanford emerald thruster. This mission is a 100kg total space craft that is using a propulsive attitude control system for the specified life time. A LEO is utilized.

Two issues need to be addressed to fully investigate the mission usefulness of the colloid thruster. First, is the Stanford emerald thruster a representation of a typical, or even more importantly the state of the art thruster. This colloid thruster, while perhaps being the most developed in recent decades (space qualified model), is not the most technologically advanced colloid thruster in development for space use. The busek ST-7 colloid thruster system has better performance parameters (especially in the areas of system dry mass and specific impulse), but as of the writing of this document has not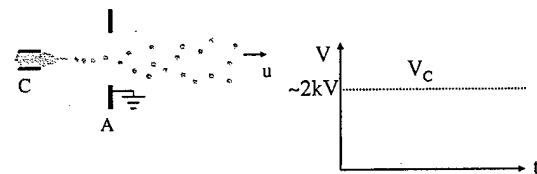 been developed sufficiently to compare with the performance numbers quoted for the other micro-propulsion devices listed. The colloid thruster performs as advertised in the missions described above. For higher thrust as well as higher energy (ISP) situations, there are engineering design challenges that must be overcome, i.e.very large arrays (VLA) of colloid needles for high thrust and micro-power supplies for high ISP thrusters.

Concept

Colloid engines are electric space propulsion devices in which droplets of a conducting fluid, typically doped glycerol or formamide, are electrostatically accelerated through a potential difference. Typically, the charged droplets are extracted from a hollow needle, which is biased with respect to an extractor gate by around 2 kV. When biased beyond its onset voltage the conductive fluid on the needle tip forms a Taylor cone-jet[1]; downstream, the jet breaks up and the particles are extracted. After extraction, the charged droplets may exit the device, or go through a second electrostatic acceleration stage, once again on the order of kV.

The concept presented here differs from a traditional colloid engine by using multiple accelerator gates biased alternately at a much lower AC voltage to linearly accelerate colloid droplets after extraction from the needle. Fig. and Fig. show these configurations.

The fluid particle droplets are accelerated in alternating sets of gates with an AC voltage. Provided the gate spacing is 'tuned' to the frequency of the extracted droplets and to the AC voltage, this configuration allows an unlimited number of acceleration gates in a thruster.

Fig. 3. Schematic of a typical colloid engine and extraction voltage.
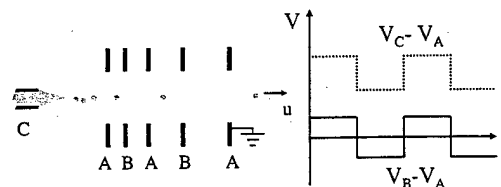
Fig. 4. Schematic of a colloid engine with electrodynamic linear accelerator and accelerator and extraction voltages.

Governing Equations and Theory

Critical parameters for the design of the acceleration system are the gate voltage, spacing, and frequency. Following are the governing principles for the colloid linear accelerator. Most are based on simple electrostatics as every particle is in between two charged grids, and the voltage on those grids is constant for the time the particle is between them. Based on colloid technology[2,3] and fundamental electrostatics the specific impulse is:

$$I_{SP} = \sqrt{2\frac{q}{m}\frac{NV_A}{g^2}} \qquad (1)$$

Where q/m is the charge to mass ratio, N is the number of gates, and V_A is the acceleration voltage per gate (assuming a square wave and that all gates have the same voltage). Correspondingly, the thrust is:

$$F = \dot{m}I_{SP}g = \dot{m}g\sqrt{2\frac{q}{m}\frac{NV_A}{g^2}} \qquad (2)$$

Fig. shows the thruster performance increase by using many (N) rather than 1 acceleration gate. For this analysis, the extraction parameters q/m and $\dot{m}$ can be described by empirical solutions[4,5,6] such that a preliminary estimate of performance may be determined using the equations above. Couple this preliminary extractor information with the previous accelerator performance analysis and a good understanding of the system emerges; results are given in Figs 6-7.

Assuming the droplet has initial velocity of zero, the geometry and spacing of the first gate, X_{G1}, may be determined simply. X_{G1} depends on the frequency, f, and vice versa:

$$X_{G1} = \sqrt{\frac{1}{2}\frac{q}{m}V_A\left(\frac{1}{f}\right)^2} \qquad (3)$$
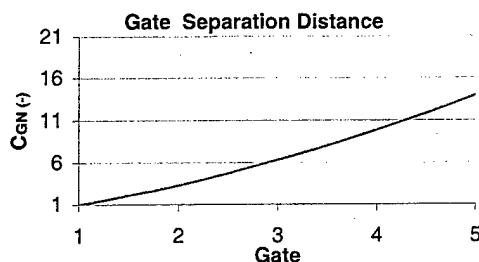
$$X_N = C_{GN}X_{G1} \qquad (4)$$

Fig. 8. Gate separation distance coefficient, CGN, versus gate number.
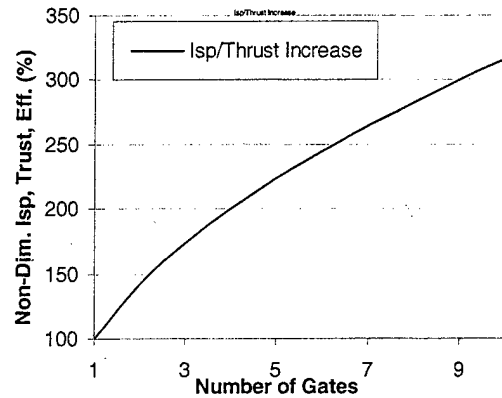
Fig. 5. Performance increase due to multiple gates versus single accelerator gate. Assumes constant extraction parameters and gate voltages.
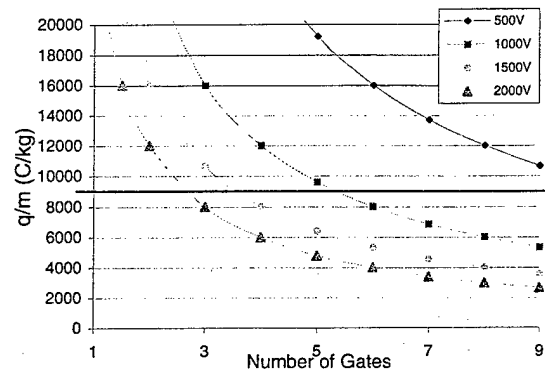
Fig. 6. Charge-to-mass ratio required for Isp=1000s and X_{G1}=1mm. 9000 C/kg is an expected operational target
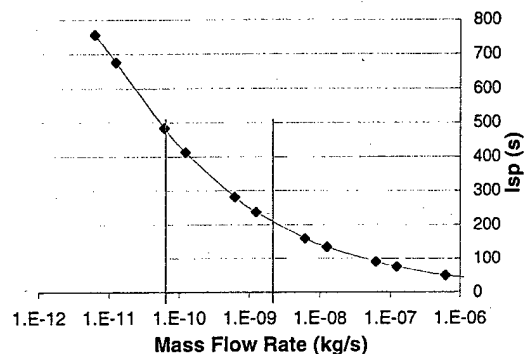
Fig. 7. Relationship between Isp and mass flow rate for a 5-gate accelerator and extraction at 1500V. Noted is the flow rate region of interest .

This gives the gate spacing between the extractor and the first gate. However, gate spacing is not linear along the length of the accelerator, and once the first gate spacing is determined, the rest must be spaced according to the following:

C_{GN} has been numerically computed, and is given versus gate number in Fig. 8.

Using these relationships, it can be shown that voltage can be totally dependent on frequency (for a constant q/m) and independent of gate spacing, i.e. the voltage and Isp can be throttled mid-mission without a geometry change within the acceleration system.
This paper discusses a square wave as the accelerator voltage signal, but it may be possible (with a ~5% accelerator efficiency loss) to use a sine wave, thereby eliminating the need for high power rectifier circuits all together.

<center>### Comparison with Traditional Colloid Engines</center>

This concept retains the performance benefits of a colloid thruster, namely potentially high Isp, high acceleration efficiency (70%+), simple acceleration physics, throttleability, and scalability (ability to miniaturize). In addition, the AC linear accelerator allows a reduction in operating voltage and increased variable operating parameters. This may simplify the power processing electronics significantly by a) not requiring a DC rectifier or other complicated switching mechanism, and b) eliminating the presence of high voltages. Potentially, a small oscillator is all that would be required, which could be miniaturized much more easily.

In terms of expected performance, this concept is similar to colloid engines being developed currently[7] and can operate with 70%+ efficiency at Isp's between 500-1500s with 10's of μN per needle. The needles can be arranged in an array to develop a thruster capable of mN thrusts. Some penalty must be paid for the additional mass of the accelerator stages, however.

The colloid linear accelerator engine still has the same disadvantages as typical colloid thruster: complicated flow system, potential gate clogging, and beam neutralization requirement. However, depending on the mission, the efficiency and mass savings over other micro-thrusters may balance out.

<center>### Design Complications</center>

Using multiple gates in a colloid engine by itself adds very little design complication, however the pulsed nature of the device does. In order to separate the droplets into groups or individual droplets the extractor must be pulsed, and there is, so far, little empirical data for this process.[8] Also the start and stop transients must all be addressed as to their effect on lifetime (clogging) and efficiency.

Furthermore, the design may be sensitive to droplet q/m. If the droplets do not have a uniform and predictable q/m, the multi-gate accelerator concept will not work properly.

Another design complication may be the high frequencies required. Fundamentally, the system requires frequencies near the exit velocity divided by the gate spacing. For 1mm spacing, and I_{sp} around 1000s, 10+ MHz frequencies are required. Even voltages of around 50V are relatively high for this frequency. One possible approach would be to use piezo-electric oscillators. Nevertheless, this is considered to be a very difficult problem inherent to this concept.
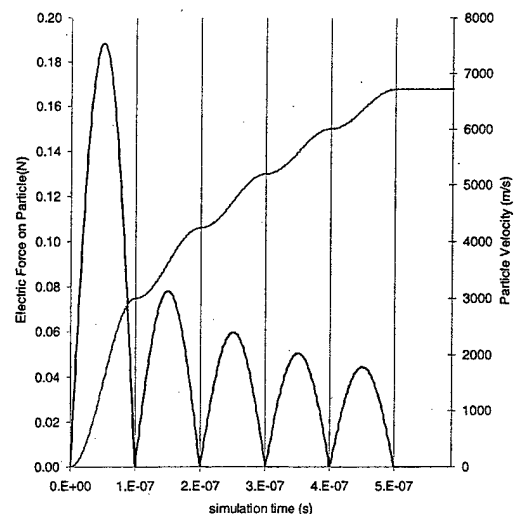

Fig. 9. Example of a 5 gate sinusoidal linear accelerator.

Investigation into design-performance sensitivities

As this concept is looked into to greater detail the need for a comprehensive understanding of how much manufacturing and design considerations (the definitions of these will be described later) effect the performance parameters in this analytical analysis of the linear accelerator system. In order to try and quantify this effect a first order particle tracking simulation has been put together. We simulate the "correct" gate positioning for the mean colloid parameters and then run a simulated particle through the system. In this way we can map the velocity distributions due to changes in gate position, particle parameters, and different acceleration voltage profiles. The following example is for a perfect particle (design charge and mass) in a 5-gate system under a sinusoidal acceleration voltage.

The first performance parameter looked at is the distribution in the charge to mass ratio of the droplets. The droplets in the following charts have an average charge to mass ratio of 5000 C/kg and an initial velocity of zero, and are accelerated with a constant (per gate pair) acceleration voltage. The graph shown displays the normalize Isp change due to % change in charge to mass ratio. It can be seen that with only a few gates an increase in charge-to-mass provides little (or maybe positive) increase in Isp, however even small losses in q/m provide large Isp and therefore performance losses. The main reason for this is that if the q/m is too low then the particle does not get the required acceleration to get the gate when the voltage shifts. This means that it not only does not get the full energy of the voltage in positive acceleration, but in fact it 'catches' the other polarity of the shifting voltage and loses speed until it gets to the gate. For the particles that have too high of a charge to mass ratio, they get to the gate too early and in the cases it many gates they end of with a large amount of deceleration. To try and characterize this effect in a more comprehensive way we applied a Gaussian distribution (with a give distribution width) of particles through the accelerator and then examined the Isp change. See figure 11. There are several obvious trends that come out of this analysis; first, the more gates the worse the problem in a relatively simple way (double the gates, about double the error for a given distribution width). Second, the Isp loss due to droplet irregularity seems to asymptote.
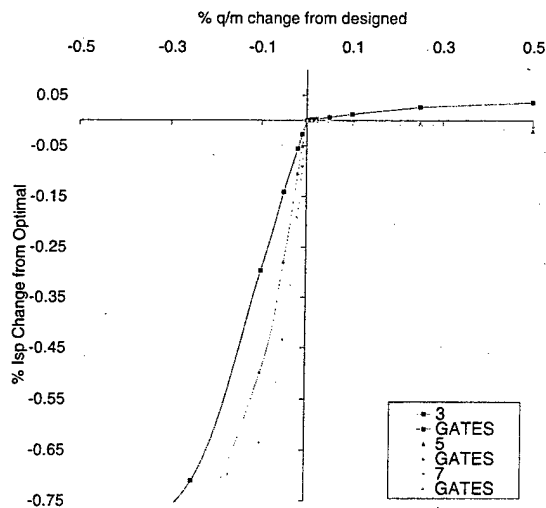

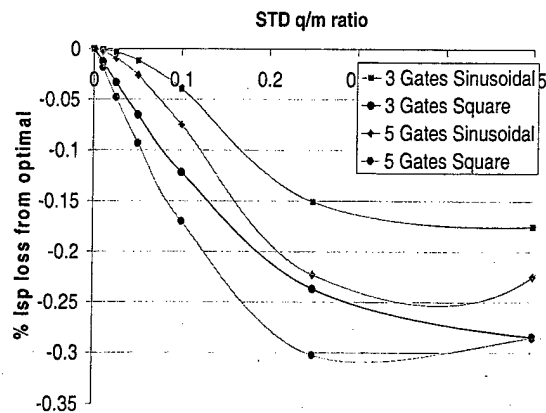Fig. 10. Isp change due to q/m for a single particle

Fig. 12. Isp change due to q/m for a distribution of particle parameters at a sinusoidal acceleration voltage.

Another important consideration is the form of the acceleration voltage. So far only two acceleration wave forms have been looked into, the square wave and the sinusoid. Figure 12 compares using the square and sinusoidal acceleration voltages in the linear accelerator, with some interesting results. What is discovered is the damage of having non-ideal particles is tremendously reduced. In most cases by half, and perhaps by as much as three-fourths. The answer to that is in the location of the acceleration of the particles. As can be seen in figure 5 most of the acceleration of the particles happens well in-between the gates far away from the edges, and consequently, for the particles that are positioned slightly off, far away from the deceleration effects of being out of sequence.

Fig. 11. Isp change due to q/m for a distribution of particle parameters

The gate spacing sensitivity was more complicated issue. One possibly significant concern with this linear accelerator is the manufacturing issues associated with how accurately the gates are spaced.

The same type of simulation (as in the q/m) was run only now with a varying gate positioning error. As seen in figure 12, we can see the same sort of trends as in the charge-to-mass investigation, however this time the performance seems to be much more dependent on the deviation. For example, 1% position error yields 3% Isp loss for 3 gates and 25% for 10 gates, and 5% position error yields 18% Isp loss for 3 gates and 60% for 10 gates! These are very serious performance losses, which will have an impact in the real design of one of these systems and need to be considered fully. One point to note, however, is that a sinusoidal acceleration voltage had similar effects on the performance losses, with savings as much as 50%.

It has been shown that the system performance specifications are highly dependent on the operating and manufacturing characteristics of the linear accelerator. The charge to mass ratio distribution had a relatively small effect (especially when driven with a sinusoidal voltage), however the gate spacing has a huge effect on overall system performance, and must be kept within tight tolerances (few %) in order to be feasible.

Fig. 13. Isp change due to gate spacing

Experimental Design Considerations

In looking at preliminary designs for an experiment as well as thruster concepts some hardware considerations must be taken into account.

First the power supply is a high frequency high voltage (even 500-1000V is still high) that is proportional to the relationship (5) where delta-x is the spacing of the final gate. It can be seen that needed is a MHz or at least 100+kHz 1kV power supply that is still relatively efficient. While several companies are able to do close to this (Mide, American HV, EMCO, etc.), they may not be able to do is cost effectively or on the same mass scales as traditional miniature DC power supplies, thereby negating a benefit of the linear accelerator system.
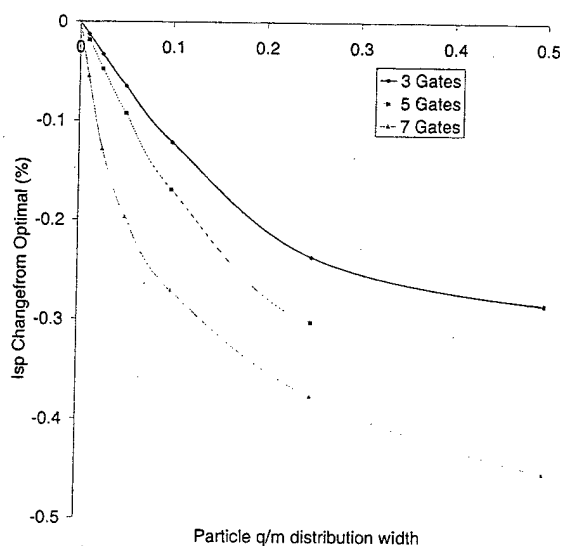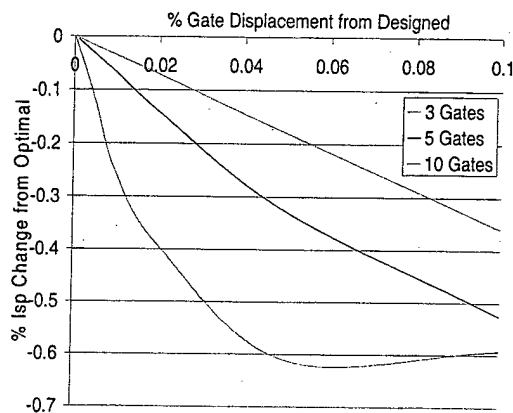
Another significant concern is unintended breakdown during an experiment. Depending on the spacing, voltage, and operating frequency atmospheric gasses can ionize in a system like the linear accelerator. For the regimes that are being discussed here, this may happen even at very low background pressures with the fundamental driving relationship being the distance between the gates. If the background pressure required is too low, it may not be cost effective or realistic in a spacecraft environment to do further research on this acceleration concept.

$$f \cong \frac{I_{SP} g}{\Delta x_N} \qquad (5)$$

A preliminary analytical investigation can be done based off of analysis in Gas Discharge Phyiscs[11] by Yuri Raizer. At vacuum level background pressures a tradition breakdown (townsend discharge) will not happen at the voltages we are considering. However, discharge may happen as a result of secondary electron emission between the gates. For an AC system that is an especially important effect. If we define a cut-off frequency for which the electrons that are emitted from the surface do not fully cross the electrode boundary and gains energy in the next cycle we can examine the conditions for breakdown. As a 0-th order estimate, assuming an emitted electron energy of 100eV (for a requirement for 'efficient emission') the breakdown frequency is:

$$f_b \approx \frac{80}{d[cm]} MHz \qquad (6)$$

$$E_b \approx \frac{120}{d[cm]} V / cm \qquad (7)$$

This is very discouraging for the design of this type of system. Eq's 6-7 imply that for d on the order of cm or tens of cm a maximum acceleration frequency (before breakdown) would be a few MHz (the same order of magnitude as our thruster). Also, the breakdown voltage is an order of magnitude less than our system (1kV), thus implying that the emitted electrons would have more energy than we have assumed and thereby hasten the cascade effect. One must additionally note that materials and material conditions are extremely important in secondary electron emission, as surface roughness and material work function have a very large effect on emitted current.

A realistic experiment would yield several very important benefits towards the design and implementation of this concept. First of all, the understanding of the two main concerns above, power supply and experimental arcing. A validation of the performance enhancements and the ability to start investigating the mechanical difficulties of production, alignment, and operation could begin.

Conclusions

This paper has attempted to introduce a design for a multi-gate AC colloid thruster that has the potential to decrease complexity and operation voltage of a colloid thruster while retaining their excellent performance characteristics. There are many engineering challenges ahead for this design. A few have been investigated in this paper, and have indeed found to be significant, namely manufacturing accuracy and experimental testing concerns. However, the concept of the multiple-gate AC linear accelerator is general, and may also be considered for use on other electric propulsion devices. For example, ion engines may be able to benefit more from this technology. In the ion engine case, q/m is more consistent and predictable, therefore eliminating some of the problems mentioned above.

The fundamental advantage of this technology is that it utilizes AC operation and multiple gates to lower the operating voltage, while retaining the performance and throttleability of an electrostatic thruster. In addition, it also enables higher performance with the same, tested, propellants and at the same operating acceleration voltages.

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